GEOTECHNICAL ASPECTS OF COASTAL EROSION

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1. INTRODUCTION

Coastal erosion is a serious problem throughout the world, both in developing and developed countries. The social and economic consequences of coastal erosion can be substantial in many cases. The economic consequences of coastal erosion reflected in the loss of land, property and ocean resources can be quite severe, especially for countries where the coastline is longer such as Australia and Japan. The nearshore ocean has been utilized for purposes such as transportation and recreational facilities whereas the land behind the coast has been developed to support agriculture, industry and housing. In order to protect these multi-faceted activities, a variety of engineering works have been installed. Thus, the coastal erosion has been taking place not only due to natural conditions but also due to increasing human activities.

The natural causes of coastal erosion are due to severe storms, hurricanes and typhoons, sea level rise and reduction in sediment supply. Some of these causes have been attributed to greenhouse effect. As property losses increase, a variety of protective measures are being developed. However, an understanding of the behavior of the coastline and the effects the protective measures have, are often lacking. Identification of the problem of coastal erosion has therefore led to a recognition of the need for quantitative evaluation of coastal change and to develop efficient methods for the management of coastal problems (Dyer, 1986).

The subject of coastal processes has tradionally received the attention of geomorphologists whose approach was essentially deductive and descriptive (Horikawa, 1988) and the coastal engineers whose interests were mainly related to wave action, wave induced currents, sediment transport and coastal structures such as breakwaters. However, the detailed mechanism of coastal processes is an extremely complicated phenomenon involving the interaction of coastal geology, wave action, variation of sea level and sediment transport both long-shore and cross-shore. Due to this complexity, a quantitative prediction of coastal change has been considered to be a difficult problem. Recently, the coastal engineers have made advances in the field of nearshore hydrodynamics and sediment transport. However, there is still a barrier for the development of predictive models for coastal evolution due to the lack of appropriate criterion for *coastal erosion*, which is principally a *geotechnical aspect*.

In the past, the prediction of coastal evolution was mainly done by relying on coastal experience in similar cases or on the results of hydraulic model tests. Empirical methods involve forecasting based on observed trends of evolution of the coast or estimating it by comparison with the evolution of other beaches. This method may be simple but it is not possible to make a quantitative prediction. In hydraulic model tests, the evolution can be studied under controlled conditions using scale models but they involve scaling problems. In addition, they require expensive facilities and a great deal of labour and time (Horikawa, 1988).

Sediment transport is generally more complicated than the motion of waves and currents. In the case of waves, the governing equations are available and the difficulty is only in solving these equations efficiently and accurately. Whereas, in the case of estimating sediment transport, reliable equations have not been formulated. For example, for many years, the calculations for longshore sediment transport have been based on CERC formula (Kamphuis, 1991) which relates the longshore sediment rate to the longshore wave energy flux. It should be realized that such a simple model does not include parameters like grain size and bed morphology. Similarly, in the case of cross-shore modelling, simple empirical rules (Dean, 1977) do not fully describe the dynamic behavior of the cross-shore profiles. During the last decade, the development in coastal sediment transport research has changed from simple phenomenological descriptions to numerical models in which the flow as well as the resulting sediment transport are simulated properly (Hanson and Kraus, 1991).

Due to the availability of high speed, large capacity computers and the development of sophisticated computational methods, it is possible to develop predictive numerical models for coastal evolution. In order to develop a numerical simulation model, the physical processes must be appropriately formulated mathematically, for example, the coastal geology may be rock, sand or cohesive material. A rocky coast presents no serious problem. A sandy coast or beach is easily deformed by the action of water and in this case, the sediment transport, has been fairly well defined. However, cohesive material presents a complex situation because of its erosion characteristics due to wave action as well as sediment characteristics, since the cohesive soil may be dry, partially saturated or fully saturated.

The complete solution to the problem of coastal evolution involves the calculation of waves, nearshore currents, sediment transport and erosion of coast. As a first step, the nearshore wave field is to be computed for the prescribed wave conditions and tidal changes. Next, the computed wave field many be used for estimating distributions of radiation stresses and near-bottoms velocities-Then, the nearshore currents are computed from the wave field. The nearshore wave and current fields are utilized for calculating sediment transport. Since the sediment particles are highly sensitive to hydro-dynamic field, accurate flow models are necessary. Finally, the transport model, flow model and coastal erosion model have to be combined together.

Thus, the major aim of this article is to discuss the geotechnical aspects of the coastal erosion rather than providing a complete solution for the complex problem of coastal evolution. For the sake of completeness, a rudimentary discussion on other aspects such as wave motion and sediment transport will be presented in the next sections.

2. MODELS FOR WAVES AND CURRENTS

2.1 Waves

The wind blowing on the ocean creates waves and these wind waves, once generated, propagate over a long distance toward a coast. The constant supply of energy from this continuous source is the main cause of the short-term change in the coast-line. Wind waves are irregular and random in amplitude, period and direction. The energy for the fluid motion in the nearshore zone is mainly due to the wind waves. Outside the surf zone, the incident waves are represented by finite amplitude waves. The wind waves that approach a coast from off-shore as incident waves are known as gravity waves with periods less than 20 sec. On the otherhand, the infragravity or long waves have periods of 20 to 200 sec. It is generally argued that the nearshore is not controlled by the incident waves but by the infragravity waves. However, the governing equations for infragravity waves have not been very well defined.

The wave equations have been developed a long time ago and the simplest is due to Airy. It is known as Airy's first order or linear theory and predicts a wave profile that is sinusoidal. It provides an adequate description of wave height and length changes during the shoaling transformations. Stokes developed the second order theory which predicts a surface profile that is composed of two sinusoids and generates an asymmetrical wave shape. In practice, real waves are randons and somewhat more complex. Therefore, it is conventional to use spectral analysis to determine the graph of energy against frequency from time series. The result is known as the power spectrum of the wave field. Since a large number of frequencies are present, spectral analysis offers a powerful tool.

In the past, the nearshore wave field has been computed using wave energy equation and wave ray methods. Since these methods are not applicable for general conditions, other mathematical models for computing wave transformation under combined refraction, diffration and breaking have been developed. Wave breaking is one of the important phenomena in coastal process. In order to determine the coastal change, it is necessary to correctly compute the nearshore waves, particularly in the surf zone.

The wave model can be based either on linear wave theory or nonlinear wave theory. If linear theory is adopted, it will give a wave height generally smaller than that of actual finite amplitude waves. It has been found that the wave field computed by linear model gives better estimates than nonlinear models for quantities such as radiation stresses and nearbottom orbital velocities.

2．2 Currents

It is important to compute the currents by a model which takes into account the relation with the preceding wave analysis and the succeeding sediment transport analysis.

When waves break at an angle to the shoreline, they generate a longshore current flowing parallel to the shoreline, confined to the nearshore zone between breakers and shoreline. Komar (1976) states that mass transport currents may be responsible for producing a net shorewards transport of sediment close to the seabed. A number of equations have been developed to predict the longshore current velocity on the basis of energy flux model, momentum flex model and mass continuity model. Essentially, if waves approach the shore at as angle, there will be a component of radiation stress that is directed in a Iongshore direction. This spatial gradient in the momentum must be balanced by an opposing force and this force leads to the generation of a longshore current. Among others, Longuet-Higgins (1970) adopts this concept of radiation stress.

It is extremely difficult to develop an equation for longshore current based on energy because it is known that only a small percentage of wave energy is required to drive the longshore current. The occurrence of mass transport in progressive wave is known but the precise volume of water which propagate towards the shoreline due to this phenomenon is difficult to predict. It is reasonable to assume that the momentum of waves must drive the mass to produce longshore currents.

Komar presents a simple equation by which longshore current velocity can be evaluated, along similar concepts to those of Longuet-Higgins.

$$\nu_l = 2.7 u_m Sin\alpha_b Cos\alpha_b \qquad (1)$$

where ν_l is the long shore current at mid-surf position

u_m is the maximum value of horizontal orbital velocity evaluated at breaker zone.

and α_b is the breaker angle.

Larson and Kraus (1991) have developed a numerical model fore the nearshore wave transformation and longshore current, based on the concept of Baum and Basco (1986) but for random waves. They obtained the governing equations for cross-shore and longshore currents from the vertically integrated, time-averaged momentum equations for nearshore water motion. these equations include wave and wind driving forces, wind direction, bottom friction stress and lateral mixing terms.

3. SEDIMENT TRANSPORT MODEL

In order to predict the change in coastline, various models have been developed. These models include both kinematic and dynamic elements. The kinematic element simply ensures the conservation of volume of sediment whereas the dynamic element attempts to predict the changes due to the forces taking place, such as elevated mean water level, storm waves or long-term sea level rise.

Sediment motion is generally more complex than the motion of waves and currents. The sediment transport involves the two-phase problem-the fluid phase in which the solid phase tends to settle to the bed. The problem requires the understanding of the process which is the erosion of the coast by wave-induced flow field, transportation and deposition of sedimentary particles.

Among the various models available for conservation of volume of sediments, such as Bruun, Edelman, Dean etc., Edelman's has been found to be more realistic (Dean, and Maurmeyer).

The sediment transport occurs both cross-shore and longshore. Longshore transport has received a far wider attention due to the construction of structures such as breakwaters which act as dams to the shoreparallel transport. It causes a build-up of the beach on the updrift side and a corresponding erosion in the down drift direction. Longshore transport is also known as shoreparallel transport, littoral drift or transport. It is accepted now that the wave-induced longshore currents are primarily responsible for longshore transport. Various empirical formulae have been proposed for longshore current, for example, Komar and Inman (1970). These formulae rely on a presumed correlation between the longshore transport rate and a measure of the longshore component of the incident wave energy. One such formula is

$$I_l = 0.77(ECn)_b Sin\alpha_b Cos\alpha_b \tag{2}$$

where I_l is the immersed weight sediment transport rate and $(Ecn)_b$ is the wave energy flux evaluated at the breaker zone.
It is to be noted that Equ (2) applies only to sand transport produced by an oblique wave approach.

Inman and Bagnold (1963) proposed a mord general expression for sand transport by combined waves and currents, as

$$I_l = 0.28(ECn)_b Cos\alpha_b \frac{\nu_l}{u_m} \tag{3}$$

Kamphuis (1991) conducted hydraulic model experiments for alongshore sediment transport and stated that the sediment transport rate is a function of a combination of wave, fluid, sediment and beach-profile parameters. Thus, a general expression is

$$Q=f(H,T,\bar{\alpha},d,\rho,\mu,g,x,y,z,t,\rho_s,D,m) \quad (4)$$

where Q is alongsliore sediment transport rate
H is wave height
T is wave period
$\bar{\alpha}$ is angle of approach
d is depth of water
ρ is fluid density
μ is fluid viscosity
t is time
ρ_s is sediment density
D is grain size
m is beach slope

He concluded that the sediment transport rate is proportional to wave energy (in fact, H^2), is a function of beach slope and depends only slightly on grain size.

Dally and Dean (1984) has proposed a finite difference model for suspended sediment transport which takes into account the wave period, wave height, sediment fall velocity and friction coefficient, initial bottom profile and slope of the face. They concluded that this model provides an insight into sediment transport problem even though it is not completely accurate.

The sediment in the coastal zone may contain particles ranging from gravel or sand to silt or clay. The behaviour of cohesive sediments is complex as they are affected by the hydrodynamic field, the chemical composition of suspending fluid and the physio-chemical properties of sediments. The suspended clay particles become more cohesive as the salinity of the sediment suspending water increases and the collision of cohesive particles with each other can result in the formation of larger aggregates. Cohesive sediments undergo various processes including flocculation/aggregation, deposition, consolidation, erosion and advective/dispersive transport (Pathirana et. al., 1994).

In the transport model, the advective/dispersive transport of suspended sediments can be expressed in terms of concentration of suspended sediment. If the concentration is assumed to be low, then the transport model and the flow model can be decoupled. Otherwise, they have to be solved together.

4. EROSION CRITERIA

4.1 Cohesionless Material

In the classical beach erosion problems where the sediment is principally sand, the erosion criterion is based on the critical shear stress for the onset of sediment movement. If the maximum shear stress at the bottom exceeds the critical shear stress, then it is assumed that a certain volume of sediment will be set in motion. The bottom shear stress is calculated on the basis of friction law for which the bottom roughness and the size of sediment grains have to be defined. At present, this model is mainly empliirical.

4 . 2 Cohesive Material

A cohesive sediment bed can vary in thickness from one centimeter to one meter. The upper portion (a few cm) is usually soft with high water content and is generally in a state of partial consolidation. Consolidation influences the critical shear stress and hence the rate of erosion.

Before cohesive soils can be eroded, the bond between interparticles must be broken. For this to happen, the critical shear stress must be exceeded. This is the main difference between cohesive soils and cohesionless soils where the resistance to erosion is due to gravity only. The rate at which erosion proceeds when the shear stress at the bed exceeds the critical shear stress is also important.

Erosion studies indicate that depth-averaged suspended sediment mass concentration, C, increases linearly with time, t, during erosion, corresponding to a constant rate of surface erosion. The erosion rate can be expressed in terms of time-rate change of concentration as

$$\varepsilon=H\frac{\delta C}{\delta t} \tag{5}$$

where H is the total depth of water.

A commonly used erosion rate expression for uniform but generally more dense deposits (Ariathurai and Arulanandan, (1978)) is

$$\frac{\delta C}{\delta t}=M\left[\frac{\tau_b-\tau_c}{\tau_C}\right] \qquad for \quad \tau_b\geq\tau_c \tag{6}$$

where M is the erosion rate constant which i s defined as the increase in the rate of erosion for an increase in the interface fluid shear by an amount equal to the critical shear stress of that soil.

τ_b is the time-mean value of the bed shear stress under which erosion occurs and τ_c is the critical shear stress.

The constant, M, has the same units as the erosion rate and varies from soil to soil.

The principal factors affecting the critical shear stress are eroding fluids, the temperature, the presence of organic matter and the stress history. It has been found that the moisture content or consolidation pressure has little effect on the erodibility characteristics of saturated soils. The tests carried out on over 200 samples by Ariathurai and Arulanandan indicate that the erosion rate constant, M, lies in the range 0.003gm/cm^2•min to 0.03gm/cm^2•min.

Parchure and Mehta (1985) carried out experimental investigations to study the erosion behaviour of soft cohesive sediment. Their analysis of experimental results yielded a relationship of the form

$$\frac{\delta C}{\delta t}=\varepsilon_f \exp\left[\alpha(\tau_b-\tau_s)^{\frac{1}{2}}\right] \tag{7}$$

where ε_f is the floc erosion rate α is the factor which is inversely proportional to temperature, τ_b is the time mean value of bed shear stress and τ_s is the shear strength.

The floc erosion rate, ε_f is the value of ε when, $\tau_b-\tau_s=0$ when no mean flow velocity dependent surface erosion occurs. The values of the parameters α and ε_f vary significantly for various soils. According to the test results of Parchure and Mehta, the value of α varies from 13.6 to 18.4m/$N^{\frac{1}{2}}$ whereas the value of ε_f varies from 0.5 to 3.2 $\times$ 10^{-5}gm/cm^2 min.

4.3 Deposition

Krone (1962) has proposed a simple deposition law in the form of

$$\frac{\delta C}{\delta t}=\frac{W_S C}{H}\left[1-\frac{\tau_b}{\tau_{cd}}\right] \tag{8}$$

where Ws is the settling velocity of sediment particles, which depends on the concentration and τ_{cd} is the critical shear stress for deposition.

4.4 Settling velocity

As stated in section 4.3., the settling velocity influences the deposition rate. Settling velocities of cohesive materials are related to suspension rather than grain size.

$$\begin{aligned} W_S &= Constant & C &< C_1 \\ &= K_1 C^{\eta} & C_1 &< C < C_2 \\ &= W_{S_0}[1-K_2 C]^{\beta} & C &> C_2 \end{aligned} \tag{9}$$

where K_1, η, K_2 and β are constants dependent on the sediment composition and the suspending flow field. W_{S_0} is the reference settling velocity, C_1 and C_2 are concentrations depending on the type of sediment-fluid mixture.

5. CONCLUDING REMARKS

A general discussion on the basic mechanism of coastal evolution is presented from the presently available information. The discussion has been concentrated specifically on the *geotechnical aspects of coastal erosion.*

As stated in the introduction, the coastal evolution is a very complex problem. In fact, the erosion itself consists of three phases. The first phase is the solid phase related to the deformation and damage of the saturated porous medium, subjected to dynamic forces. Therefore, one has to model this phenomena on the basis of Biot's dynamic consolidation theory. The second phase is with respect to erosion and segregation. The third phase is the flow and the sediment transport. Due to the interdependent nature of these three phases, it may be necessary to adopt some sort of iterative procedure to solve the governing equations defining the problem of coastal evolution.

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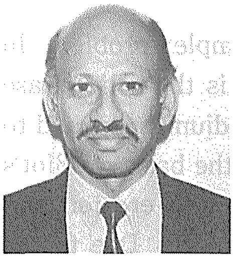

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